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The Impact of Satellite Infrared Sea Surface Temperatures on the FNOC EOTS Regional Gulf Stream Analysis

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Foreword

Remote sensing of the oceans from spaceborne platforms has dramatically enhanced our capability to identify strategic ocean environmental parameters on the global scale. Satellite sea surface temperatures have been measured from space for more than a decade and are now refined to an accuracy better than 0.7°C. With more than 60,000 to 90,000 retrievals readily available each day, this data source can be extremely advantageous to naval operations.

This report deals with the impact that infrared sea surface temperatures have on the Fleet Numerical Oceanography Center's ocean thermal structure analyses. Particular attention is focused on the capability of satellite retrievals to map strong frontal zones that cover mesoscale regions of interest. Whereas past efforts have identified qualitative changes due to satellite retrieval assimilation, this report investigates the quantitative impact by comparison to independent in situ data sets.

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Executive Summary

In July 1987, two Expanded Ocean Thermal Structure (EOTS) analysis runs were made daily at 12Z for 5 consecutive days. These runs were made offline at the Fleet Numerical Oceanography Center for the EOTS Gulf Stream region. All available satellite multichannel sea surface temperature (MCSST) retrievals, ship reports, and expendable bathythermograph observations were assimilated into the first analysis, with MCSSTs withheld from the second to determine satellite data impact on the analysis. Aircraft-launched expendable bathythermograph (AXBT) data from coincident Regional Energetics Experiment flights were used as independent ground truth. The analysis results and input data sets were compared to the AXBT data.

This study shows that MCSST data significantly add to the accuracy of front and eddy mapping by tightening up strong frontal gradients and reducing the impact of relatively noisy ship data. The reliability, the accuracy, and the quantity of MCSSTs far exceed that of ship reports. This difference is evident in the better identification of significant oceanographic features by the satellite-aided analysis.

It was found that the accuracy of the regional EOTS analyses can be severely degraded when the only available MCSST data are over 48 hours old. Navy plans to produce MCSSTs should improve the arrival time of these data and allow for a shorter time window of data to be assimilated by EOTS. Implementation of Navy MCSST production should be vigorously pursued to ensure accurate regional analyses.

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I. Introduction

U.S. Navy operational activities, such as the antisubmarine warfare effort, ship track routing, and search and rescue missions, benefit from accurate knowledge and prediction of the three-dimensional ocean thermal environment. In response to this need, the Fleet Numerical Oceanography Center (FNOC) generates an operational hemispheric and regional scale thermal analysis that can be readily utilized by these activities. This analysis system, the Expanded Ocean Thermal Structure (EOTS), provides a full three-dimensional analysis of the ocean thermal structure from the sea surface down to 400 m (Clancy and Pollak, 1983).

The EOTS system provides real-time or hindcast input to any program that requires information about the thermal structure of the ocean. Perhaps the most important operational application of EOTS is to provide input to programs that determine sound propagation paths. Knowledge of such strategic information has direct impact on the operational capabilities of all Navy surface and subsurface vessels.

The EOTS surface analysis is also input as a lower boundary to operational atmospheric models. Combined with land-based meteorological observations, this information provides atmospheric models with an accurate knowledge of initial surface temperatures throughout the world.

The ability to map out the thermal structure of the oceans has been severely hampered in the past due to the sparsity of in situ observations. Because of satellite-derived sea surface temperatures (SSTs), the number of observations now available for analysis has markedly increased, paving the way for improved analyses and analysis techniques. This report demonstrates the impact of satellite-derived SSTs on the operational FNOC EOTS analysis system. More specifically, it details the areas of impact and identifies methods for further improvement of the analysis.

II. The EOTS Analysis System

EOTS analyses are produced twice a day for the northern and southern hemispheres, and daily for most of the regional analyses. The analysis system utilizes a polar stereographic projection grid for each of the regional fields with a maximum dimension along either axis of 125 grid points. Table 1 details the operational analysis regions currently available at FNOC. Also included are the respective runtime schedules and grid-point resolutions.

Table 1. Expanded ocean thermal structure (EOTS) analyses.

Region	Resolution (km)	Schedule	SST-Bottom	SST	PLD	TEOTS
N Hemisphere	320	2/Day	•	•		•
S Hemisphere	320	2 Day	•	•		•
Norwegian Sea	40	Daily	•			•
W Mediterranean	40	Daily	•			•
E Mediterranean	40	Daily	•			•
Gulf Stream	20	Daily	•			
N Kuroshio	32	Daily	•			
S California	40	Daily	•			
Caribbean	32	Daily	•			
Indian Ocean	80	Daily	•			
S China Sea	40	M,W,F,Sa		•	•	
Mid Pacific	54	Tu,Th,Su		•		
S Kuroshio	40	Tu,Sa		•	•	
Labrador Sea	40	M,W,F,Su		•		
Iberian Sea	40	M,W,F,Su		•		

SST—Sea Surface Temperature
PLD—Primary Layer Depth
TEOTS—EOTS is cycled with TOPS forecast model

The EOTS analysis assimilates expendable bathythermograph (XBT) reports, ship/buoy observations, and satellite multichannel sea surface temperature (MCSST) retrievals to construct a three-dimensional thermal structure analysis of the ocean. The assimilation is performed through utilization of the Fields by Information Blending (FIB) technique (Holl et al., 1979).

The analysis is based on the parameterization of the vertical temperature profile of the ocean. The parameters used were selected to identify significant temperature variations in the vertical while also maintaining an analysis continuity in the horizontal. EOTS utilizes 26 predefined parameters located between the surface and 400 m to map out the thermal structure of the ocean (Clancy and Pollak, 1983). These parameters are displayed in Figure 1. The parameters include 18 standard level temperatures or temperature differences, as well as eight floating level temperatures determined by the Primary Layer Depth (PLD). The PLD is the depth of the main or seasonal thermocline, depending on which feature is more prominent at the time.

The separation of the fixed-depth surfaces is nonuniform so that greater resolution is provided in the near-surface waters than in deeper waters. This technique is used because deep ocean water is less variable over time and space. The eight floating parameters are positioned in a manner to best define the thermocline temperature gradient. Combining the fixed-level parameters with the floating parameters and blending vertically and horizontally via the FIB technique produces a three-dimensional analysis of the ocean thermal structure.

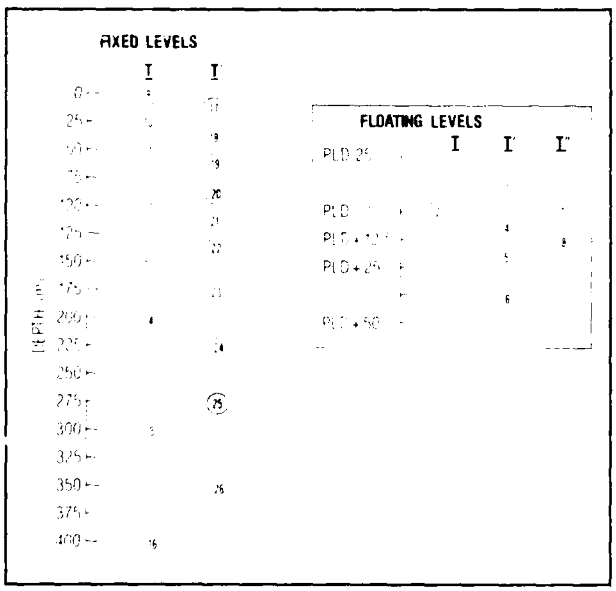

Figure 1. The twenty-six expanded ocean thermal structure (EOTS) parameters.

A. Data Input to EOTS Analyses

1. The Bogus Message

The Gulf Stream EOTS regional analysis is designed to accept the input of front and eddy positions derived primarily from human interpretation of infrared satellite imagery. This information is input to EOTS via a "bogus" message that is generated at the Naval Eastern Oceanographic Center (NEOC). The bogus message reports the Gulf Stream north and south wall locations, as well as the frontal temperature gradients. The location and size of warm and cold eddies are also defined. The operational product is produced once a week through the analysis and interpretation of infrared imagery and any additional information obtained from advantageously positioned ship, buoy, and XBT reports. Figure 2 is a plot of the features defined in the bogus message produced for the period from July 9 to July 15, 1987.

An altimeter-derived sea height analysis using the GEOdesy SATellite altimeter has recently been added to aid in locating fronts and eddies. This analysis was developed at the Naval Ocean Research and Development Activity as an operational demonstration product. It was recently transitioned to the Naval Oceanographic Office for full-time operational use. The product is now produced once a day and transmitted to NEOC for use in developing the weekly bogus message.

This analysis is based on the detection of sea surface height differences along the satellite flight path. These differences are calculated from the information contained in the return pulse of the satellite radar altimeter. The location of frontal boundaries and eddies is determined by interpretation of the sea surface changes seen by the altimeter. These changes are a reflection of the assumed geostrophic balance between surface-height-induced pressure gradients and the Coriolis force. For example, the altimetric signature of a cold core eddy is a depression of the sea surface that reflects the counterclockwise (cyclonic) rotation of cold rings in the northern hemisphere.

This product's greatest contribution is best demonstrated over cloud-covered locations. Under these conditions front and eddy detection by infrared imagery is severely hampered, since clouds block the transmission of sea surface infrared radiation to space. Because the radar altimeter transmits and receives at a microwave frequency, clouds pose no major hindrance to data collection by this technique.

The front and eddies bogus plays a major role in the present EOTS analysis scheme. Bogus information is included into the EOTS analysis as a heavily weighted input, which in effect forces the analysis to position the fronts and eddies at the message-reported latitude-longitude locations. Without the bogus, EOTS cannot produce a Gulf Stream or eddy field that is realistic

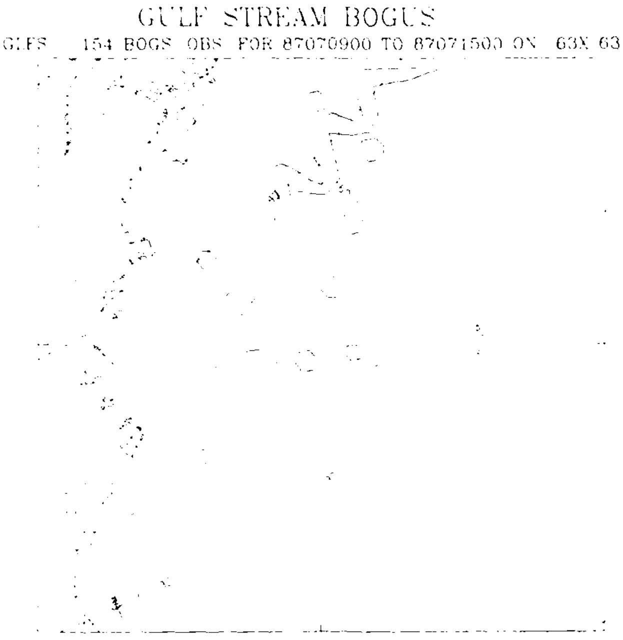

Figure 2. Plot of front and eddy locations as reported in NEOC bogus message for July 9 through 15, 1987.

or acceptable in terms of defining tactically significant features of Navy interest (Hawkins et al., 1986). The XBT, ship/buoy, and MCSST data by themselves cannot define the fronts and eddies when assimilated by the FIB technique. The bogus message thus provides the primary means of identifying these tactical features in EOTS.

Front and eddy locations may move appreciably from one weekly message to the next, especially when the analysts are working with limited satellite and in situ data sets during a period of large Gulf Stream instability. EOTS would benefit if bogus messages were generated as often as conditions warranted. This would improve both bogus message continuity and the EOTS analysis product.

2. The Data

The regional EOTS analyses incorporate a variety of data cutoffs for each input data type: XBTs (48 hours), ship/buoy data (72 hours), and MCSSTs (60 hours). These time windows were selected based upon the distribution of available observations and the processing time delays inherent in each data type. Climatological SST values are incorporated into the EOTS analysis as a first guess and to fill in data-void areas. This data set is derived from the Master Oceanographic Observation Data Set (MOODS), which contains more than four million observations taken over a 65-year period (Teague et al., 1987).

For use in EOTS, monthly averaged climatological temperatures are assigned to each regional grid point location. The value chosen each day by the analysis is obtained by linearly interpolating between the temperatures of the two closest months. Figure 3a displays the climatological temperature contoured to 1°C resolution for the Gulf Stream on July 15. Climatology is used as a first-guess field if the previous day's analysis is not available. It is also used in areas that are void of recent observations.

MCSSTs are retrieved each day on an orbit-by-orbit basis at a resolution of 8 km and accuracy of 0.6°C (Strong and McClain, 1985; McClain, 1986). With observations available up to twice a day from any cloud-free location, this method of data collection has provided a greatly expanded global coverage of SST information. MCSSTs are received at FNOC from the National Environmental Satellite and Data Information Service (NESDIS) via the National Meteorological Center (NMC). Figure 3b shows a typical MCSST distribution for the Gulf Stream region in July.

The distribution of MCSSTs is highly dependent upon the location of clouds, which block the transmission of ocean surface infrared radiation to the satellite sensor. This blockage accounts for a wide variability in the number of retrievals from day to day. For the Gulf Stream region, 1000 to 2000 MCSSTs are typically retrieved during any given 60-hour period. During persistently cloudy periods, the distribution may drop below 500 MCSSTs. However, during clear weather, the number of MCSSTs retrieved has exceeded 5000.

XBT measurements are typically collected at infrequent intervals along commercial shipping routes. Many ocean areas are left entirely unmonitored due to the relative sparsity of these observations. Figure 3c contains a distribution of unclassified Gulf Stream region XBTs. The three reports shown here reflect the poor coverage offered by ships at sea. The amount of subsurface information available is obviously limited. Although some classified XBTs are assimilated by the operational EOTS runs, the quantity is most often too small to noticeably improve the analysis.

Ship and buoy observations are received at FNOC from NMC on a regular basis. These reports provide adequate surface coverage of the major ocean shipping lanes, most coastal locations, and selected remote ocean buoy stations. A ship and buoy data distribution plot for the Gulf Stream region in July is displayed in Figure 3d.

This data set contains many more buoy reports than ship observations because National Oceanic and Atmospheric Administration (NOAA) platforms regularly report every 1 to 3 hours compared to the 6-hourly ship report schedule. Since each fixed buoy location could have up to 72 reports available in the data file, EOTS searches for only the most recent observation. The redundant buoy reports have also been eliminated in the distribution plot.

Although the quantity of SST data available is important for generating a reliable analysis product, the

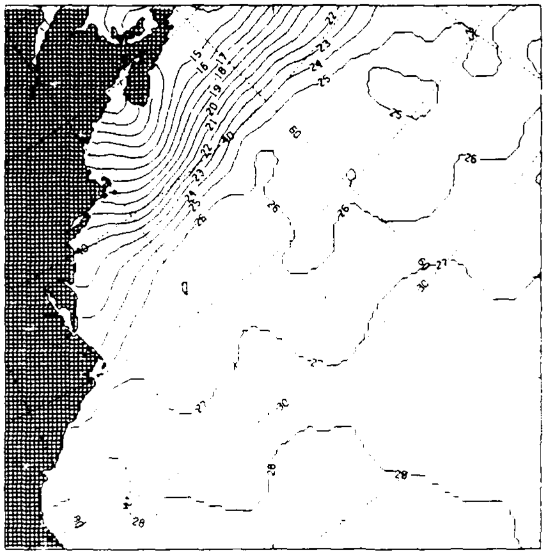

Figure 3a. Climatology surface temperatures as analyzed for July 15, 1987.

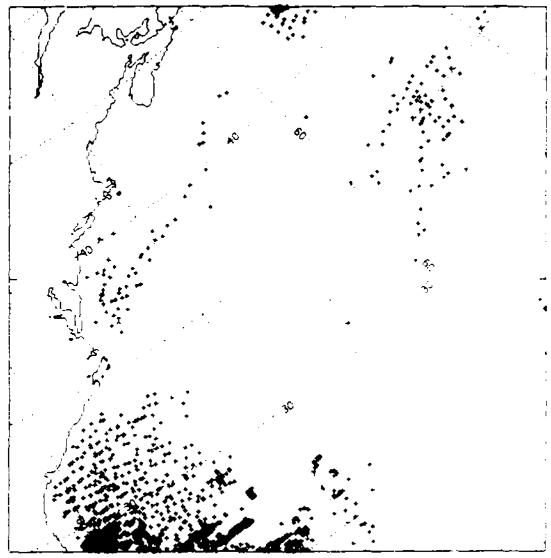

Figure 3b. Sixty hours of MCSST retrievals for the period covering July 11-13, 1987.

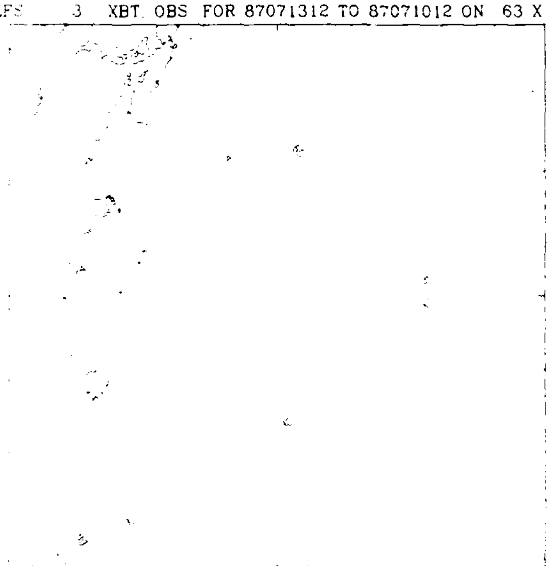

Figure 3c. Forty-eight hours of unclassified XBT observations for July 11-13, 1987.

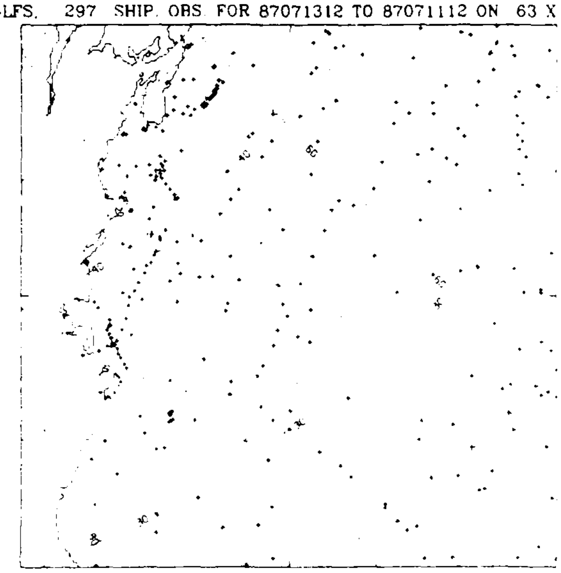

Figure 3d. Seventy-two hours of ship reports for July 10-13, 1987.

accuracy of all the data sources is even more important. Current Navy performance specifications for XBTs require the temperature accuracy to be within 0.2°C. Operational comparison of XBT data studies to conductivity-temperature-depth (CTD) measurements shows XBTs to be accurate within 0.17°C (Seaver and Kuleshov, 1982; Heinmiller et al., 1983).

MCSST accuracy as determined by matchups with global drifting buoy observations in June 1987 is displayed in Figure 4 (Walton, 1987). With very low mean difference (less than 0.2°C) and a scatter less than 1°, MCSSTs are an accurate way to obtain large quantities of global SSTs.

Ship observations normally show a consistently low mean difference compared to surface truth, but are a highly variable data set due to the numerous practices used to obtain SSTs. The scatter among ship observations compared to NOAA's National Data Buoy Center moored buoys has been found to exceed 3.5°C (Earle, 1985).

With regard to this information, EOTS utilizes a weighting process in which each data type is assigned a weight based on its accuracy. XBT data are assigned the maximum weight of 1.0, followed by MCSSTs at 0.71, and then ship reports, which receive a weight of 0.57. In data-sparse areas, climatology is used by the analysis.

III. Method of Analysis

EOTS was run offline at FNOC for 5 consecutive days in mid-July 1987. The tests described here determined the quantitative impact of satellite SSTs on these runs. This determination was made by running two parallel versions of EOTS offline, where one version had access to all available data (MCSSTs, XBTs, ship/buoy, and bogus information), but the other denied the use of MCSSTs.

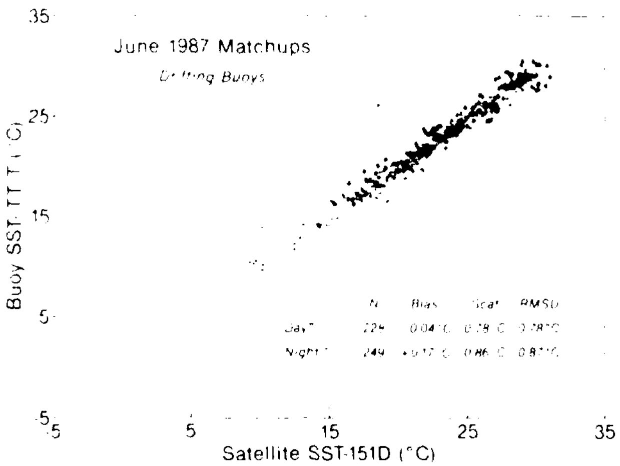

Figure 4. Matchup of satellite MCSSTs versus drifting buoys for June 1987.

Each version was initialized on July 13 using climatology as a first guess. Each succeeding day then used the previous day's analysis result as its first guess. This process was repeated throughout July 17 for both versions.

This procedure coincided with three Regional Energetics Experiment (REX) flights over the Gulf Stream in which numerous aircraft-launched XBTs (AXBTs) were dropped into the region. These flights occurred on July 13, 15, and 17 (Teague et al., 1988). Figures 5a-5c show the AXBT drops plus all unclassified bathythermograph data taken within the 48 hours preceding 12Z on each of these days. AXBTs comprise the majority of the data sets; the flight tracks are clearly evident in each figure.

These AXBT data were not assimilated into the EOTS analysis, thus providing an independent ground-truth data set for comparative techniques. Navy performance specifications for AXBTs require temperature accuracy within 0.55°C using the Navy-specified temperature-to-frequency conversion equation. AXBTs have been found to be accurate to within 0.2°C to 0.5°C, dependent upon the conversion equation used (Boyd, 1986).

The results from both analyses are qualitatively compared by producing difference fields between them. The cause of these differences is determined by analyzing the various input data sets for specific disagreements. These data sets are then compared to available AXBT data to derive conclusions about the differences.

Statistical comparisons include daily comparison of MCSSTs and ships to AXBTs dropped within 25 km and 24 hours. Statistics calculated are the mean difference, the standard deviation, and the root-mean-square (RMS) error. Each daily analysis produced with MCSST data is compared to AXBTs dropped within 25 km and 24 hours of each grid point. This comparison is also performed for the daily analysis produced without MCSST data. Scatterplot diagrams are constructed for specific cases to aid in interpreting the statistics derived.

IV. Comparison Results

Figure 6a is a contoured map of the SST field for July 17 generated by EOTS with access to all data types. This field is contoured at 1°C resolution. Figure 6b is the EOTS SST field run without MCSSTs for the same period. These two figures display the qualitative difference that satellite SSTs can have on EOTS after only 5 days. The relative noisiness of the Sargasso Sea seen in Figure 6b as compared to Figure 6a is a reflection of the large scatter associated with ship observations.

The two figures also exhibit a difference in the definition of the shelf-slope front near 41°N to 42°N. This

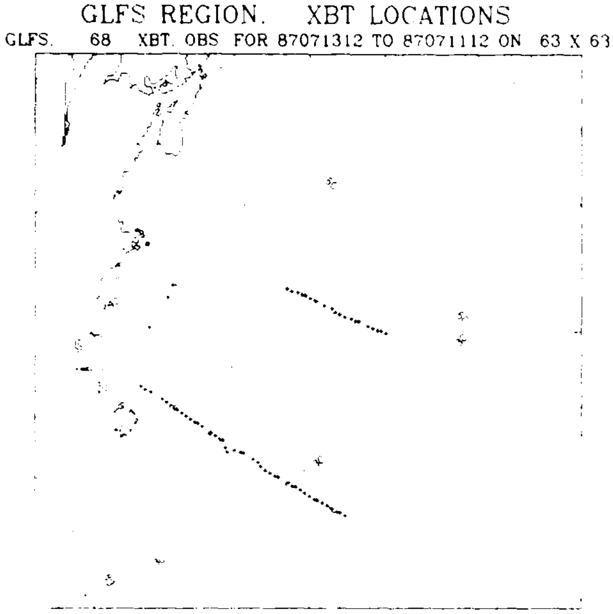

Figure 5a. Plot of REX AXBT drop locations on July 13 plus unclassified XBT reports for July 11-13, 1987.

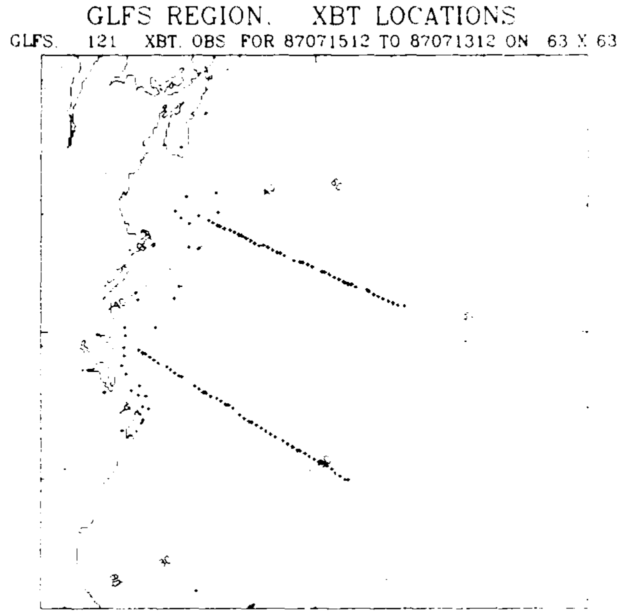

Figure 5b. Plot of REX AXBT drop locations on July 15 plus unclassified XBT reports for July 13-15, 1987.

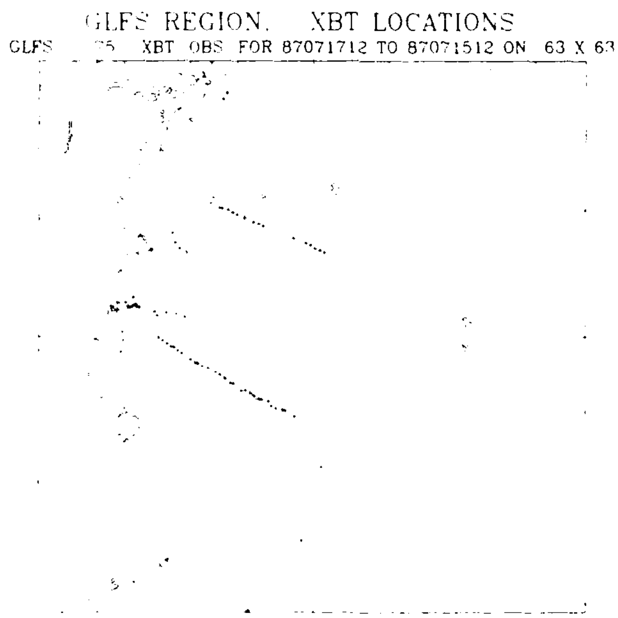

Figure 5c. Plot of REX AXBT drop locations on July 17 plus unclassified XBT reports for July 15-17, 1987.

front is typically quite sharp and can have a 2°C to 3°C or larger gradient within two 20-km grid points. The EOTS field that assimilates MCSSTs shows a sharper, more realistic front than the field that does not assimilate MCSSTs into the analysis. This sharper analysis reflects the importance of the higher density of observations available through MCSSTs. With more available observations in the shelf-slope front, the gradient and frontal position are better defined.

MCSSTs retrieved between 0Z and 23Z on each of the 5 days (July 13-17) were statistically compared to all AXBTs dropped within 25 km and 24 hours of each retrieval. This comparison was also done each day for ship observations taken between 0Z and 23Z. The results are displayed in Table 2.

The mean difference between MCSSTs and AXBTs are found to be within 0.8°C the first 2 days of the study, and within 0.2°C the next 2 days. The final day

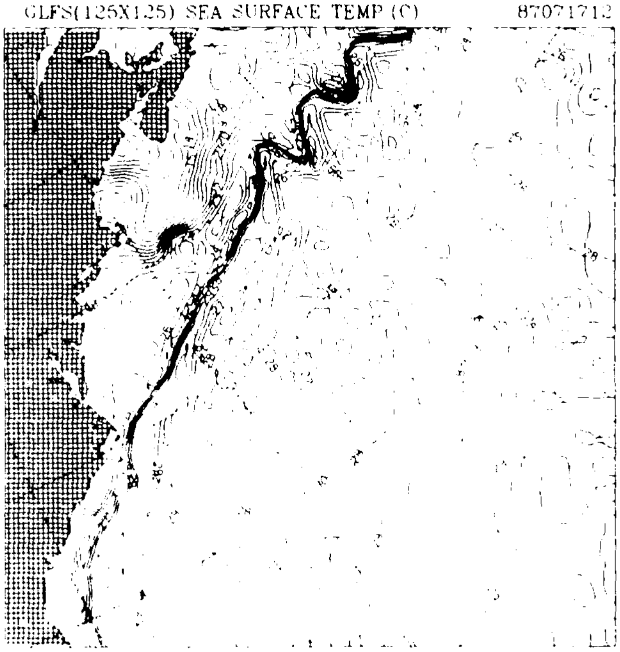

Figure 6a. EOTS analysis with MCSST data on day five of study.

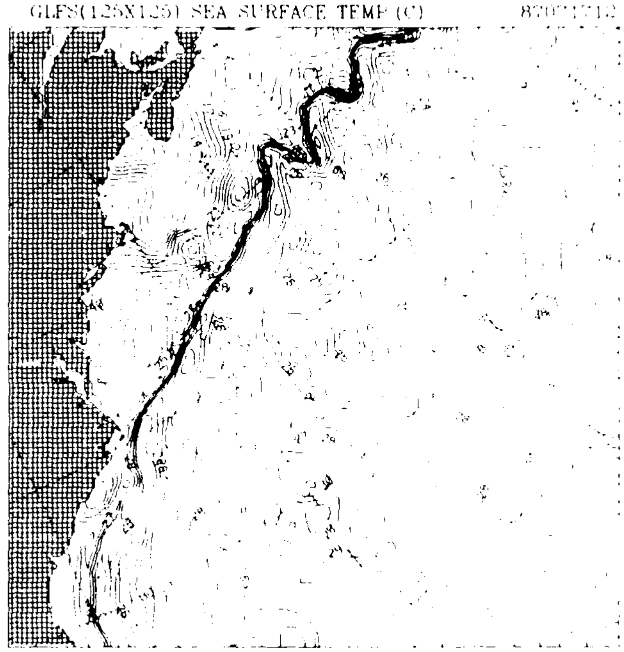

Figure 6b. EOTS analysis without MCSST data on day five of study.

of the study produced no matches with AXBTs. Cloudy conditions over the flight paths prevented MCSST retrieval within the time and distance constraints.

In comparison, the mean difference between ship observations and AXBTs is within 0.2°C the first 3 days of the study, rises to 1.3°C the fourth, and drops to 0.7°C on the final day. Although the ship mean difference is usually quite small when compared to global surface truth, these results show how ship data can possess a bias when compared to regional-scale surface truth.

The scatter and RMS differences between MCSSTs and AXBTs are found to be less than 1.5°C throughout the study period, with most days less than 1°C. This amount is consistent with the scatter for global MCSSTs in Figure 4. In comparison, the ship observations are more highly variable than the MCSSTs when compared to the AXBTs. The scatter and RMS differences consistently exceed 1.4°C, with most exceeding 3°C each day.

Assuming that the temperature differences are distributed normally, it can be calculated, on average, that less than 29% of all ship observations can be expected to be within +1°C of the nearest surface truth. In comparison, slightly more than 74% of the MCSST retrievals can be expected to be within the same range. The impact of this accuracy on a regional 20-km resolution analysis, such as the Gulf Stream, could significantly affect the identification and location of important oceanographic features.

Table 2. AXBT vs. MCSST; AXBT vs. ship

AXBT vs. MCSST					
DAY	13	14	15	16	17
Mean Diff	−.82	−.79	−.06	−.22	N/A
St. Dev.	.96	1.96	.68	.37	N/A
RMS Diff	1.23	1.55	.66	.42	N/A
# of matches	12	16	24	18	0
AXBT vs. ship					
Mean Diff	.01	−.20	.21	1.34	.67
St. Dev.	1.99	1.49	3.26	4.53	4.13
RMS Diff	1.94	1.45	3.18	4.58	3.89
# of matches	22	15	19	16	7

To study this effect, each grid point from the analysis generated using MCSST data was compared to all AXBTs dropped within 24 hours and 25 km. This comparison was also made on the analysis that did not use MCSSTs. Table 3 shows that the MCSST-derived analysis mean difference, scatter, and RMS difference are, for the most part, lower. The difference is surprisingly slight, however, with regard to the relatively greater statistical differences shown in Table 2.

The slight difference could possibly be attributed to the weight given to the MCSST data in the analysis. Although weighted higher than the ship data, the weight may be too small relative to the other weights to significantly impact on the resultant analysis. Due to the nature of the AXBT flight paths, which covered

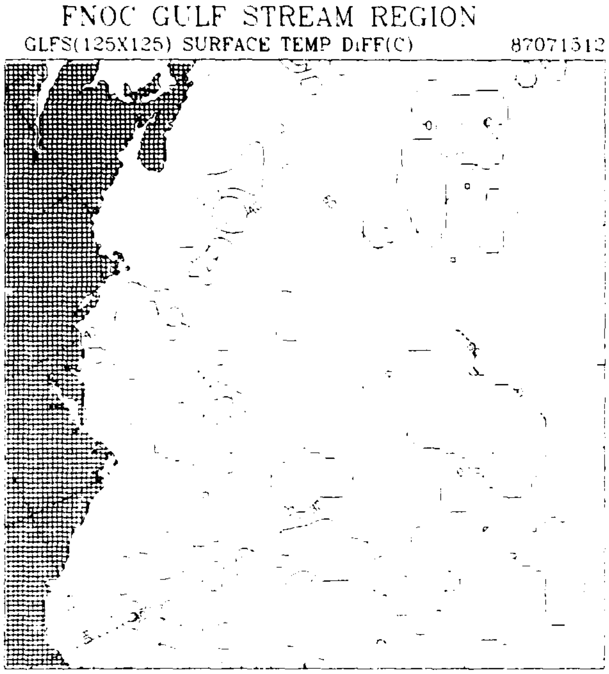

Figure 7. Difference between analyses with and without satellite MCSST data for July 15, 1987 (with–without).

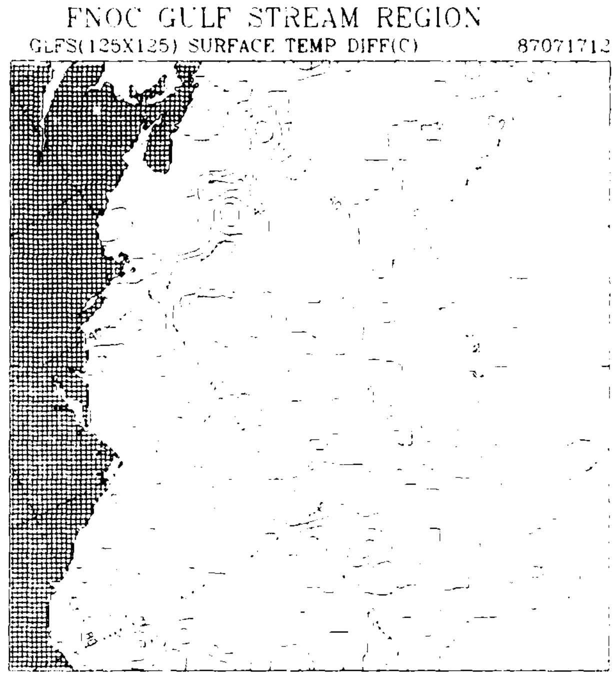

Figure 8. Difference between analyses with and without satellite MCSST data for July 17, 1987 (with–without).

Table 3. AXBT vs. analysis with MCSST; AXBT vs. analysis without MCSST.

AXBT vs. analysis with MCSST					
DAY	13	14	15	16	17
Mean Diff	−1.17	−.79	−.26	−.26	.54
St. Dev.	1.08	.92	1.91	1.81	2.17
RMS Diff	1.59	1.21	1.91	1.82	2.21
AXBT vs. analysis without MCSST					
Mean Diff	−1.38	−1.15	−.70	−.64	−.19
St. Dev.	1.02	.93	1.97	1.94	1.92
RMS Diff	1.71	1.47	2.08	2.03	1.90

the most dynamically active portions of the regional grid, the statistics could be highly influenced by differences within the Gulf Stream features.

Since the bogus is weighted high and changes only once a week, the feature positions and gradients will not change throughout the 5-day analysis period. Although an observation may actually identify the proper new location of a feature, the analysis will tend toward the bogused position instead. Update of the bogus only once a week, therefore, is obviously a weakness in the analysis. Because matches also occur outside the immediate stream environment, assimilation of MCSSTs would still be expected to improve the analysis results to a greater degree.

Difference fields were generated to delineate the specific areas of disagreement between the two SST fields. Figure 7 shows the differences between the fields (MCSST minus no-MCSST) for July 15.

Study of the data assimilated by the analyses shows that a bad ship observation at approximately 32°N, 78°W caused the field produced without MCSSTs to analyze this portion of the Gulf Stream boundary too cold. The higher weight given to MCSST data allows the MCSST analysis to properly define the south wall thermal structure.

Another area of difference is located at 39°N, 67°W. Here, the analysis with MCSST data is warmer than the analysis without MCSST data. Closer examination reveals that the MCSSTs are detecting either a warm filament along the Gulf Stream north wall or a northward advance of the north wall itself. This feature is substantiated by AXBTs dropped in the region on July 15. This feature is not defined properly in the bogus, since the bogus at this point in time is approximately 5 days old. Also, not enough ship observations were made within this vicinity for the analysis without MCSST data to define this feature well.

The Gulf Stream is a dynamically meandering boundary current that is subject to abrupt changes of location on the order of days. Until the bogus can be operationally updated two or three times a week, such changes will escape detection by EOTS unless numerous in situ observations reveal their existence.

The area of difference located at 41°N, 64°W arises from a 2°C difference between one ship observation and several MCSSTs in this area. Although no bathythermograph data exists in this region to substantiate either data type, the ship observation appears to be anomalously warm.

Figure 8 displays the differences between the two EOTS fields (satellite minus no-satellite) for July 17.

Because each analysis uses the previous day as a first guess, the lack of any new ship data in the vicinity of 32°N, 78°W allows the anomalously cold feature described in Figure 7 to continue on into the fifth day of the no-satellite analysis.

An area of difference also exists at 35°N, 70°W where the MCSST analysis is warmer than the analysis without MCSSTs. Here, all MCSSTs were found to be warmer than AXBTs dropped in the region. Closer inspection reveals that all MCSSTs are afternoon observations and consequently may be warmer than the true surface temperature due to diurnal surface layer heating.

This problem occurs occasionally during MCSST retrievals during conditions of near-calm winds and quiet seas. Satellite infrared radiation detectors sense only the temperature of the upper few millimeters, or "skin temperature," of the ocean, which under normal mixing conditions generally differs from temperature at depth by only a few tenths of a degree. Under the conditions described above, however, the skin temperature can be elevated through direct heating by the sun to as much as 2°C to 4°C more than the temperature at 1 m (McClain, 1987). This effect occurs most often in the subtropics and tropics during summer.

Another major area of analysis difference is present along the north wall of the Gulf Stream between 60°W and 70°W in the vicinity of 40°N. AXBTs dropped in this region are in better agreement with the analysis without MCSST data. Most MCSSTs in the area are much warmer than the AXBTs by more than 2°C to 3°C. Scatterplots are used to help in identifying why.

MCSSTs used in the satellite analysis were matched to all AXBTs dropped within 25 km of the retrievals. Figure 9a displays a scatterplot of all matches made. Statistics are listed for all matches within 25 km of a retrieval and also for only the closest match to each retrieval. Those matches differing by more than 3°C are designated by a boxed "x."

As seen in Figure 9a, most matches differ by more than 3°C. Closer inspection of these matches shows that not only are all the retrievals located in the vicinity of the Gulf Stream north wall between 60°W and 70°W, but that the majority of these retrievals are also 59 hours old. Only one matched retrieval is under 36 hours old. This retrieval agrees within 0.5°C of the nearest AXBT. Two retrievals a. between 36 and 48 hours old. These are plotted in Figure 9b. Both are within 0.5°C of the nearest AXBTs.

Figure 9c shows that all bad matches made are greater than 48 hours old; in this case, all are 59 hours old. To verify that these latter MCSSTs were in fact valid at the time that they were retrieved, they were matched to AXBTs dropped within this same vicinity on July 15. Figure 9d shows that retrievals within 25 km of these AXBTs are within 0.9°C agreement, validating the retrieval accuracy.

A possible explanation for these temperature differences is that the north wall of the Gulf Stream has shifted its position southward during the time between the MCSST retrievals and the AXBT observations. The older MCSSTs would then show surface temperatures to be much warmer than the younger AXBT observations in the same vicinity, which is exactly what is observed in Figures 9a through 9d.

EOTS currently generates an analysis after assimilating 60 hours of MCSST data. Due to a 17- to 20-hour delay in processing and disseminating MCSSTs from NESDIS to NMC and on to FNOC, the 60-hour window is really less than 40 hours. By the time the analysis is run, the majority of retrievals available is over 24 hours old. The impact of this delay on the EOTS analysis is apparent in the case study shown in Figures 9a-9d. Since no MCSSTs are available within 36 hours of the more timely AXBT observations, the MCSST file contains an inadequate sample of SST retrievals for producing an accurate analysis along the north wall for this period.

Because the Navy plans to produce its own MCSSTs soon, this time delay should improve, which would allow for a possible reduction in the input times of MCSST data assimilated into the analysis. Limiting the input data to less than 48 hours should prevent older data from hindering regional analyses.

V. Summary

EOTS was run offline at FNOC for 5 consecutive days in mid-July 1987. The purpose of the runs was to determine the impact of satellite MCSSTs on the Gulf Stream regional analysis generated by EOTS. Coincident AXBT, MCSST, and ship observations were statistically compared against each other and also against two separate EOTS analyses. These analyses were identical, except that one used MCSST, ship, and XBT data as input and the other was denied access to satellite MCSSTs. The AXBT data used for ground-truth comparison was an independent data set obtained from a coincident REX flight exercise. These data were not assimilated into either of the two analyses.

Results show that MCSSTs agree with the AXBT data better than the ship observations do. Less than 29% of all ship observations are expected to be within 1°C of AXBT ground truth on any day, compared to 74% of the MCSSTs. AXBT observations compared to the two EOTS analyses have slightly better agreement with the field that had access to MCSSTs. This difference, however, was not as great as the AXBT-MCSSTs vs. AXBT-ship difference, which leads us to believe that EOTS may not be making optimum use of the MCSSTs.

The analysis generated without MCSST data was much noisier than the analysis with MCSST data due to the high variability in ship observation accuracy.

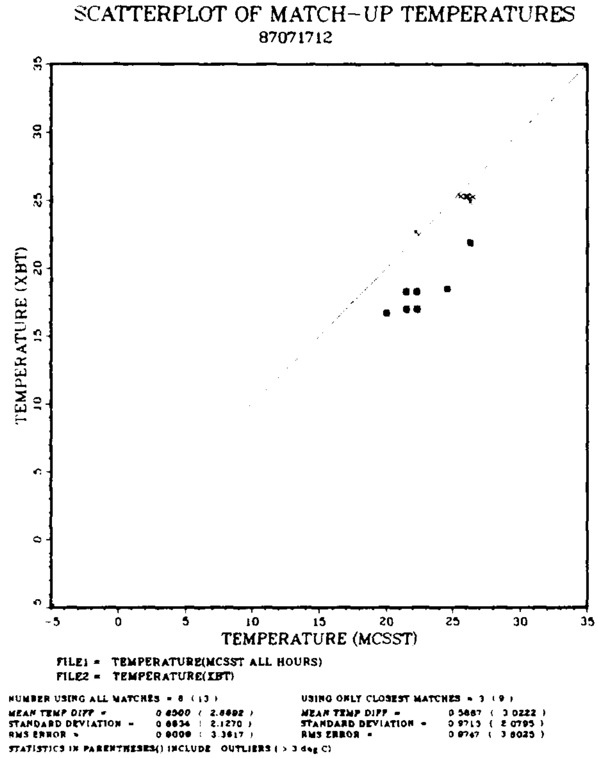

Figure 9a. Scatterplot matchup for all AXBTs and MCSSTs within 25 km and 60 hours on July 17, 1987.

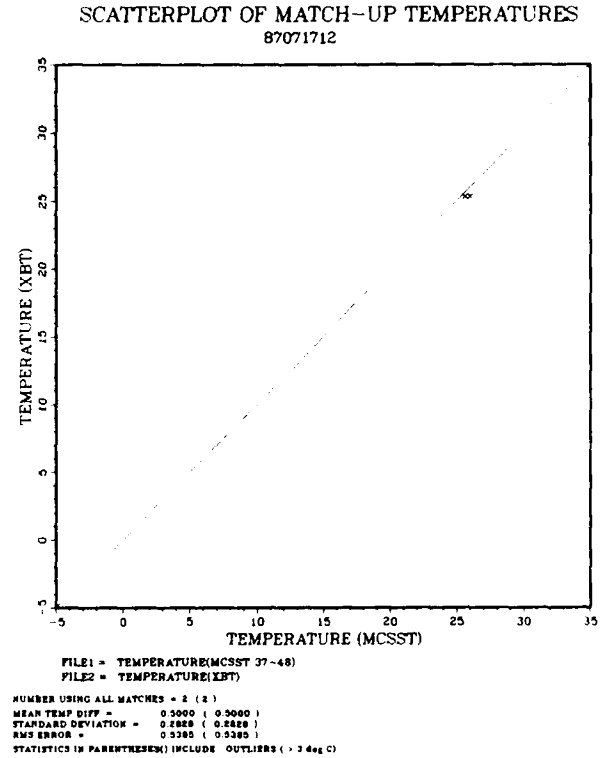

Figure 9b. Scatterplot matchup for all AXBTs and MCSSTs within 25 km and 37 to 48 hours on July 17, 1987.

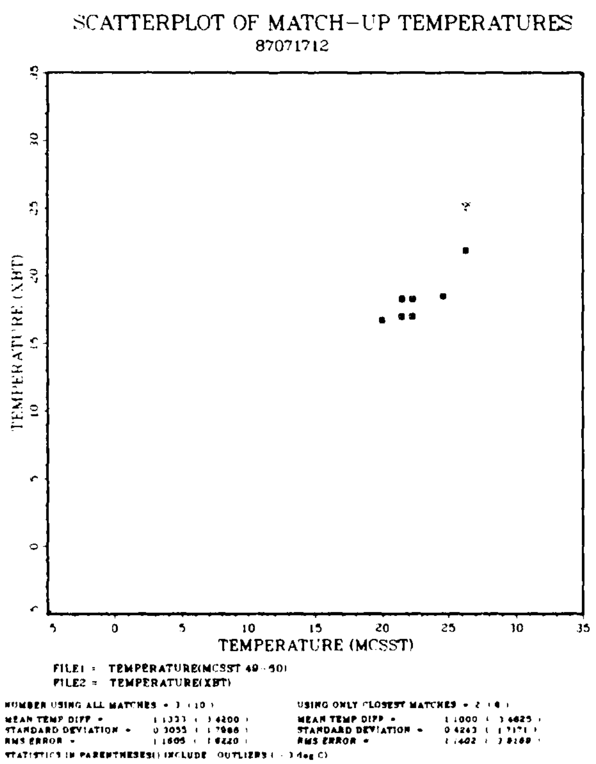

Figure 9c. Scatterplot matchup for all AXBTs and MCSSTs within 25 km and 49 to 60 hours on July 17, 1987.

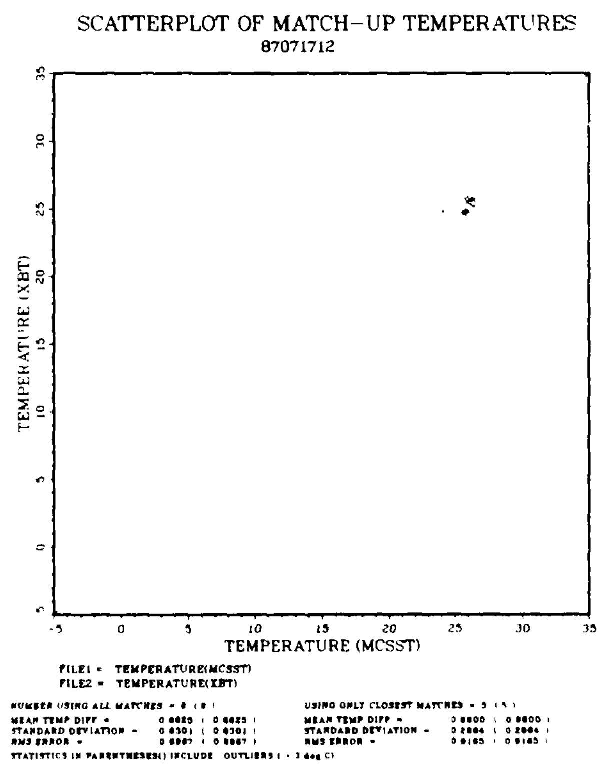

Figure 9d. Scatterplot matchup for all July 15 AXBTs within 25 km and 24 hours of the MCSSTs plotted in Figure 9c.

The MCSST-generated analysis was also able to better identify such significant features as the shelf-slope front. This capability is attributed to the relatively higher density of MCSST data available. Such high-density data are very important for locating significant oceanographic features in regional analyses.

Due to an inherent 17- to 20-hour delay in processing MCSST data through NESDIS, NMC, and FNOC, all MCSSTs used in an EOTS analysis can easily be more than 24 hours old at analysis time. The accuracy of the regional analyses can be severely degraded when the only available data are over 48 hours old. The detrimental impact of such data on the analysis was demonstrated.

The accuracy of the EOTS analysis should improve if the current data assimilation time window for MCSSTs and ships is decreased to at least 48 hours. Due to the present time delay inherent to MCSST processing, the current time window must be continued for now to ensure an adequate supply of data for the analysis. Future plans that include Navy in-house production of MCSSTs should decrease the FNOC arrival time of MCSSTs and aid in the improvement of EOTS and future analysis systems. Implementation of this effort should be vigorously pursued.

Due to the high dynamical instability of the Gulf Stream, the present bogus message implementation technique fails to keep up with stream feature changes and thus degrades the analysis. The bogus frequently locates features improperly due to the age of the information being used. To produce a more accurate daily analysis, the bogus update frequency should be increased to two or three times a week, dependent upon when conditions are favorable for new bogus generation.

MCSSTs sometimes create anomalously warm areas in the regional analysis if the areas are experiencing diurnal surface-layer heating during retrieval time. This problem occurs occasionally during summer afternoons at certain tropic and subtropic locations. Since the analysis assimilates 60 hours of MCSSTs, both daytime and nighttime retrievals are incorporated into the analysis. When large day-to-night temperature differences exist, the analysis accuracy can be degraded. A diurnal time-weighting scheme that weights the nighttime MCSSTs differently than daytime MCSSTs should be considered. This weighting scheme would weigh the daytime retrievals more for the daytime analysis, and the nighttime retrievals more for the nighttime analysis.

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In July 1987, two Expanded Ocean Thermal Structure (EOTS) analysis runs were made daily at 12Z for 5 consecutive days. These runs were made offline at the Fleet Numerical Oceanography Center for the EOTS Gulf Stream region. All available satellite multichannel sea surface temperature (MCSST) retrievals, ship reports, and expendable bathythermograph observations were assimilated into the first analysis, with MCSSTs withheld from the second to determine satellite data impact on the analysis. Aircraft-launched expendable bathythermograph (AXBT) data from coincident Regional Energetics Experiment flights were used as independent ground truth. The analysis results and input data sets were compared to the AXBT data.

This study shows that MCSST data significantly add to the accuracy of front and eddy mapping by tightening up strong frontal gradients and reducing the impact of relatively noisy ship data. The reliability, the accuracy, and the quantity of MCSSTs far exceed that of ship reports. This difference is evident in the better identification of significant oceanographic features by the satellite-aided analysis.

It was found that the accuracy of the regional EOTS analyses can be severely degraded when the only available MCSST data are over 48 hours old. Navy plans to produce MCSSTs should improve the arrival time of these data and allow for a shorter time window of data to be assimilated by EOTS. Implementation of Navy MCSST production should be vigorously pursued to ensure accurate regional analyses.

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